

Mass and Heat Transfer
Analysis of Mass Contactors and Heat Exchangers
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INSTRUCTORS MANUAL

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This material is presented as an aid to teaching an effective course in Mass and Heat Transfer using the text and this *website maintained by the Chemical Engineering Department at the University of Delaware, www.mht.che.udel.edu*. Portions of this website is constantly under development as we experiment with exercises which we are testing for effectiveness.

II PLANNING A COURSE

The text and the website are designed to teach students how to become proficient in engineering analysis by studying mass and heat transfer, transport phenomena critical to chemical engineers and other chemical professionals. The book is organized differently than traditional courses in mass and heat transfer in that more emphasis is placed on mass transfer and the importance of systematic analysis. The course in mass and heat transfer in the chemical engineering curriculum is typically taught in the junior year and is a prerequisite for the design course in the senior year and in some curricula, also is a prerequisite for a course in equilibrium stage design. An examination of most mass and heat transfer courses shows that the majority of the time is devoted to heat transfer and in particular, conductive heat transfer in solids. This often leads to overemphasis of mathematical manipulation and solution of ordinary and partial differential equations at the expense of engineering analysis, which should stress the development of the model equations and study of model behavior. It has been the experience of the authors that the “traditional” approach to teaching undergraduate transport phenomena frequently spends less time on the more difficult problem of mass transfer, despite it being an area which is critical to chemical professionals.

The material on the website will be modified and expanded as we test different approaches. Lively and interesting in-class experiences can not be effectively converted to a book, almost all of the critical interaction disappears. We have tried to partially restore this with the website. It is now only partly successful but we will keep trying. Your comments and suggestions are always welcome. The website material is coordinated with the book chapters. The activities section on the web site can be used by students on their own or as class room exercises to liven up the lectures.

At the University of Delaware, chemical engineering students take this course in mass and heat transfer the spring semester of the junior year after having courses in thermodynamics, kinetics and reactor design, and fluid mechanics. The students’ analytical skills developed through analysis of problems in kinetics and reactor design provide a basis for building an engineering methodology for the analysis of problems in mass and heat transfer. This approach is presented in two parts as illustrated in Figure I. Part I of this approach shown on the figure as Equipment Scale Fluid Motion consists of Chapters 1 through 4 of the textbook. Part II of the textbook (Chapters 5, 6 and 7) is represented by the other two elements in the figure entitled Transport Phenomena Fluid Motion and Micro-Scale Fluid Motion. Chapter 8 presents three design studies.

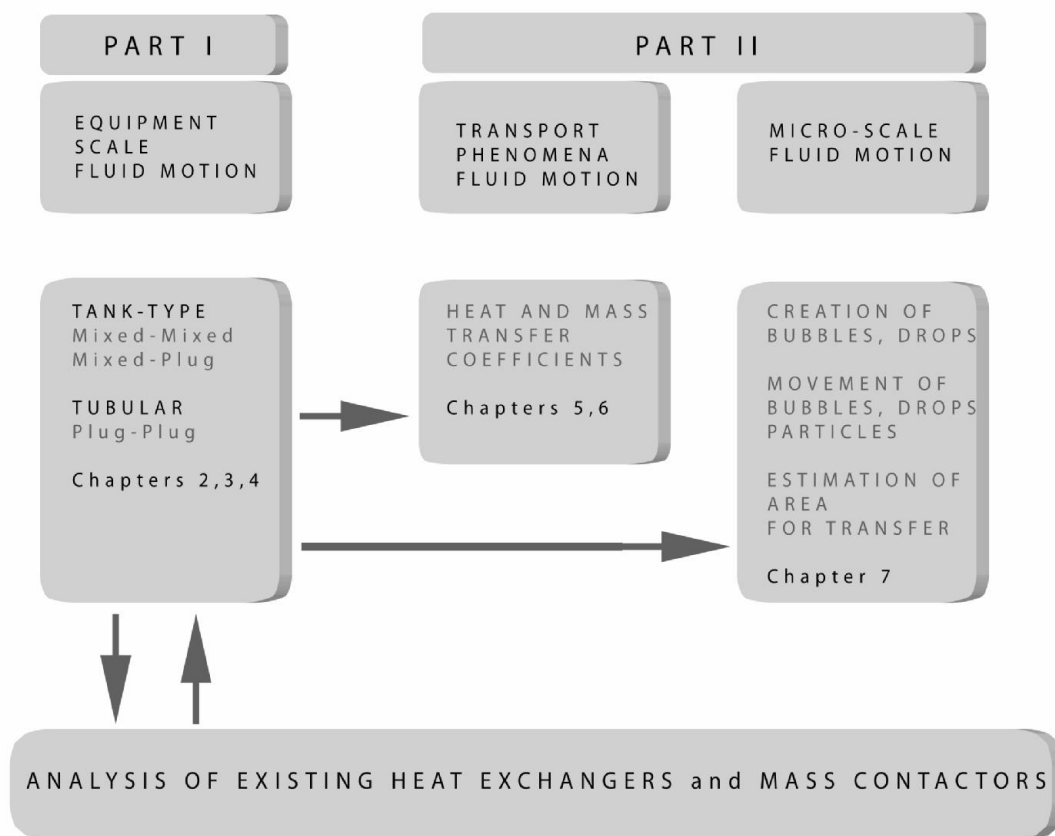


Figure I

Part I of the textbook is devoted to the analysis of reactors, heat exchangers and mass contactors in which the fluid motion can be characterized as well mixed or plug flow, Equipment Scale Fluid Motion.

Table I indicates how Chapters 2, 3 and 4 are structured and defines the fluid motions in each of these pieces of equipment. Such fluid motions are a very good approximation to what is achieved pragmatically and in those situations where the fluid motion is more complex, the Table I analysis provides useful limits on performance. The model equations developed in Part I are essential for the analysis of existing equipment and for the design of new equipment. Experiments performed in existing equipment, often at the laboratory scale, determine reaction rate constants, heat transfer coefficients, mass transfer coefficients, and interfacial area. Such experiments are necessary to complete the correlations developed in Part II. Carefully planned experiments are often necessary if the operation and control of existing laboratory, pilot or commercial scale equipment is to be analyzed.

REACTORS SINGLE PHASE	REACTORS TWO PHASE	HEAT EXCHANGERS	MASS CONTACTORS
Single Control Volume	Two Control Volumes	Two Control Volumes	Two Control Volumes
Tank Type <i>Mixed</i> <ul style="list-style-type: none"> • Batch • Semi- Batch • Continuous 	Tank Type <i>Mixed Mixed</i> <ul style="list-style-type: none"> • Batch • Semi-Batch • Continuous <i>Mixed Plug</i> <ul style="list-style-type: none"> • Semi-Batch • Continuous 	Tank Type <i>Mixed Mixed</i> <ul style="list-style-type: none"> • Batch • Semi-Batch • Continuous <i>Mixed Plug</i> <ul style="list-style-type: none"> • Semi-Batch • Continuous 	Tank Type <i>Mixed Mixed</i> <ul style="list-style-type: none"> • Batch • Semi-batch • Continuous <i>Mixed Plug</i> <ul style="list-style-type: none"> • Semi-Batch • Continuous
Tubular <i>Plug Flow</i>	Tubular <i>Plug Flow</i> <ul style="list-style-type: none"> • <i>Co Current</i> 	Tubular <i>Plug-Plug Flow</i> <ul style="list-style-type: none"> • <i>Co Current</i> • <i>Counter Current</i> 	Tubular <i>Plug-Plug Flow</i> <ul style="list-style-type: none"> • <i>Co Current</i> • <i>Counter Current</i>

Table I
Equipment Fluid Motion Classification

Another way to characterize our approach to organizing the analysis of equipment and transport problems is shown in Table II. This is presented to give guidance to the emphasis instructors might like to place on the way they teach from this textbook. Level I and Level II analyses are the first sections of Chapters 2, 3 and 4. Chapters 2 and 3 require a Level III analysis. Chapter 4 demonstrates the importance of a Level IV analysis. *The Level I II and III analysis for a mixed-mixed tank type heat exchanger and mass contactor are illustrated on the [Web Activities page](#) , which also illustrates for comparison purposes a continuous flow stirred tank reactor.*

Part II continues with Level I, II and III analysis in Chapter 5 but introduces two new constitutive equations shown in Table 1.4. Chapter 6 requires a Level V analysis to develop relationships for mass and heat transfer coefficients. This text does not deal with any Level VI issues except in a minor way in Chapter 7 which provides methods for estimating interfacial areas in mass contactors.

In teaching the material in this text it is crucial that students understand the critical role of experiment in verifying the constitutive equations for rate of reaction, rate of heat transfer and rate of mass transfer (summarized in Table 1.5). It is these constitutive equations that are used in

Chapters 2, 3 and 4 in the model equations for the fluid motions as outlined in Table I. The most critical elements in Part I of this textbook are therefore:

- Chapter I Introduction

The [game exercises](#) on the activities section of the website can be used to effectively illustrate the example in Chapter I and the critical aspects of the analysis logic presented as Figure 1.2. If you do this in class it takes at least two class periods with homework assignments. It is also an effective means of reviewing Chapter 2 for students who have taken a chemical reactor design course

- 2.1 Batch Reactors
- 2.2 Reaction Rate and Determination by Experiment

A simple example is illustrated in the [Introduction and Review of Chemical Reactor Analysis](#)

- 3.1 Batch Heat Exchangers
- 3.2 Rate of Heat transfer and Determination by Experiment
- 4.1 Batch Mass Contactors
- 4.2 Rate of Mass transfer and Determination by Experiment

	LEVEL I	LEVEL II	LEVEL III	LEVEL IV	LEVEL V	LEVEL VI
OUTCOME	OVERALL MASS AND ENERGY BALANCES	ALLOWS NUMBER OF EQUILIBRUM STAGES TO BE DETERMINED <u>BUT DOES NOT ALLOW STAGE DESIGN TO BE ACHIEVED</u>	EQUIPMENT DESIGN <u>AT THE LABORATORY, PILOT AND COMMERCIAL SCALE</u> CAN BE ACHIEVED		<u>MOLECULAR CONDUCTION AND DIFFUSION ANALYSIS ARE QUANTIFIED</u> MASS AND HEAT TRANSFER COEFFICIENT CORRELATIONS <u>ARE DEVELOPED</u>	
CONSERVATION OF MASS	REQUIRED	REQUIRED	REQUIRED	REQUIRED	REQUIRED	REQUIRED
CONSERVATION OF ENERGY	REQUIRED	REQUIRED	REQUIRED	REQUIRED	REQUIRED	REQUIRED
CONSERVATION OF MOMENTUM	NOT REQUIRED	NOT REQUIRED	NOT REQUIRED	NOT REQUIRED	REQUIRED	REQUIRED
EQUILIBRIUM CONSTITUTIVE RELATIONS	NOT REQUIRED	REQUIRED	MAY BE REQUIRED	MAY BE REQUIRED	MAY BE REQUIRED	MAY BE REQUIRED
CONSTITUTIVE RELATIONS						
RATE EQUATIONS	NOT REQUIRED	NOT REQUIRED	REQUIRED	REQUIRED	NOT REQUIRED	NOT REQUIRED
CONDUCTION DIFFUSION VISCOSITY RELATIONS	NOT REQUIRED	NOT REQUIRED	NOT REQUIRED	NOT REQUIRED	REQUIRED	REQUIRED

Table II

In our course at the University of Delaware (36 class hours) students have taken a course in Chemical Engineering Kinetics so we expect students to know how to obtain reaction rate expressions and how to use the verified rate expression in the design of continuous tank type and tubular reactors. Of course some review is always necessary because it is important for students to realize that we build carefully on the reaction analysis to study mass and heat transfer. *This review can be effectively used with the first and second sections of the game on the [Activities](#) section of the website.*

We try to limit this review to two class periods with appropriate homework.

In teaching Chapter 3 on heat transfer we believe that in addition to Sections 3.1 and 3.2 one should cover in detail the following sections which demonstrate the utility of the constitutive equation for heat transfer:

- 3.3.2.1 Semi-Batch Exchangers, Mixed-Mixed
- 3.3.3.1 Continuous Flow Tank-Type Heat Exchangers, Mixed-Mixed
- 3.4 Tubular Heat Exchangers

*There is an exercise in the Activities section of the web on deriving the model equations for the continuous flow tank type heat exchanger. We normally devote between 6 to 8 class hours to heat exchanger analysis of existing equipment where the heat transfer coefficient, U is known. *The Technically Feasible Analysis of a Heat Exchanger is in the [Activities](#) section of the Web. This can be used in class and is valuable for initiating class discussion, participation and for illustrating how U can be obtained for an existing unit.**

Correlations for U are covered in Chapters 5 and 6.

Our major emphasis in the course we teach is Chapter 4 and we believe that it deserves between 9 to 12 hours of class time. The model equations are developed for the two control volumes just as we do for heat exchangers. This reinforces the comparison which is useful to cement the students understanding of the modeling process. The major differences between heat exchanger analysis and mass contactor analysis are the equilibrium issues, the approach to equilibrium conclusions and the issues raised by direct contact of the two phases. In addition to the mass transfer coefficient, K_m , there is the interfacial area, a , to be considered. Methods to estimate K_m are covered in Chapters 5 and 6. Procedures for estimating a are given in Chapter 7.

Chapter 5 is devoted to experimental justification of the two constitutive relations commonly referred to as Fourier's and Fick's "laws." This development in Sections 5.1 and 5.2 thus parallels our discussions in Chapters 2, 3 and 4 that provides experimental evidence for the constitutive relations for rate of reaction, rate of heat transfer and rate of mass transfer. The derivations for the overall coefficients, U and K_m , in terms of individual resistances can be skipped if time is short but the resulting expressions are essential. The material on membrane diffusion may be of interest in some situations, time permitting.

Chapter 6 also contains more material than one can reasonably cover in a typical 36 hours of class time so choices have to be made depending on the emphasis one desires. It is probably necessary to cover most of Sections 6.2, 6.3, and 6.4 but one needs to avoid long lectures in which there is excessive algebraic manipulation—it is the resulting correlations which are critical. These are summarized in Section 6.4.

In Chapter 7 we treat the challenging problem of estimating interfacial areas in both tank-type and tubular mass contactors. This is an area of active research today but we have tried to present the current state of the art so this critical parameter for rational scale-up and design can be estimated.

Part II concludes with Chapter 8 presenting designs which can be completed once the mathematical models from Part I are available and methods for estimating U , K_m and a are available from Part II. This is illustrated in Figure II. These design case studies evolved from in-class, problem-based learning exercises as well as group semester project assignments, and can be used as bases for such activities.

There is a good deal more material in this text than one can reasonably cover in 36 hours of class time. We have endeavored to produce a text which gives the instructor and student maximum flexibility without sacrificing the logic of sound engineering analysis.

This book is not a reference book nor is it an exhaustive compendium of phenomena, knowledge, and solved problems in mass and heat transfer. Suitable references are provided in each chapter for further study and for aid in the analysis of phenomena not treated herein in depth. As a first course in mass and heat transfer, it is limited in scope and content by design. As an instructor, we hope you can build upon this manuscript and tailor your lectures to incorporate your own expertise and experiences within this framework to enrich the course for your students.

Instructors who wish to teach their course with the molecular phenomena as illustrated by Fourier's and Fick's "laws" can begin the course with Chapter 5 but it will be necessary to explain the rate expressions for heat and mass transfer presented in Chapters 3 and 4 if students are to understand the Chapter 5 material and the critical role it plays in the analysis of heat exchangers and mass contactors

II IN-CLASS DEMONSTRATIONS

BATCH HEAT EXCHANGER EXPERIMENT

This simple demonstration requires a constant temperature bath, a one liter bottle, a thermocouple and a watch. For a bath temperature set at 35°C the data collected in problem 3.6 were obtained by students during the class demonstration. From this data one can estimate U , the heat transfer coefficient.



SALT TABLET MASS TRANSFER EXPERIMENT

Contributed by Michelle O'Malley

The following details an experiment that may be performed in a classroom setting. In this experiment, students determine the overall mass transfer coefficient, K_m , in a solid-liquid batch system. The procedure detailed here closely follows the discussion in section 4.2 of the text.

Equipment needed:

- Conductivity probe (for example Cole-Parmer 1481-55)
- Beaker (2L or larger)
- ddH₂O
- Salt tablets (of known geometry)
- Granular salt (optional)
- Magnetic stir-plate
- Magnetic stir bar
- Timer
- Balance

1. Prior to the experiment, the mass of granular salt or salt tablets should be measured on a balance and recorded before addition to water. Ideally, the volume of the salt added to the system should also be known (or estimated) and recorded.
2. In order to correlate salt concentration in the water phase with conductivity observed, it is necessary to construct a calibration curve that allows for this estimation. This may be done by simply dissolving a known amount of salt into a known volume of water, allowing equilibrium to be reached, and recording the conductivity observed at that concentration. This procedure should be repeated for various salt concentrations, ranging from zero g/L to a value greater than the concentration to be used in the experiment.
 - a. Place a known volume of ddH₂O into a clean beaker, with a stir-bar at the bottom. Set this on a magnetic stir-plate and allow the water to be mixed at a moderate speed.
 - b. Measure conductivity in the water solution with the conductivity probe before the addition of any salt.

- c. With the conductivity probe still immersed in the water, add a known amount of salt tablets or granular salt to the solution. After allowing equilibrium to be reached record the conductivity observed at that concentration.
 - d. Plot values of conductivity vs salt concentration to obtain a standard curve.
3. In class, begin the experiment by repeating steps 2a and b. Then with the conductivity probe still in the water, add salt tablets or granular salt to the water. Record the conductivity in the water phase as a function of time at regular time intervals. A reasonable time interval is 10-15 seconds. Be careful to keep the conductivity probe in roughly the same position in the water, as fluctuations in its position may impact conductivity readings.
 4. Assemble a table of conductivity measurements as a function of time. Convert the conductivity measurements to concentrations of salt in the water phase through use of the calibration curve.
 5. Use the model equations developed in section 4.2 of the text to determine K_m from the data obtained.

Sample Experiment:

An example of data generated from this experiment follows below. In this particular experiment, two different types of salt (granular versus tablet) were dissolved in 1.0 L ddH₂O as a function of time, and conductivity measurements were made at regular increments. Four different situations were analyzed, which are given below, and data collected from the experiments are provided in Table 1.

Case I: 5 salt tablets dissolving in ddH₂O with mixing (20g total mass)

Case II: granular salt dissolving in ddH₂O without mixing (25g total mass)

Case III: granular salt dissolving in ddH₂O with mixing (25g total mass)

Case IV: 5 salt tablets dissolving in ddH₂O with mixing (5.78g total mass)

Table 1

Time (s)	Case I Conductivity (mS)	Case II Conductivity (mS)	Case III Conductivity (mS)	Case IV Conductivity (mS)
0	0.01	0.00	0.20	0.05
15	0.42	0.04	0.20	0.05

30	0.72	0.04	0.68	0.11
45	0.84	0.04	1.18	0.18
60	0.94	0.05	1.31	0.23
75	1.02	0.06	1.75	0.29
90	1.11	0.06	1.86	0.34
105	1.21	0.07	2.19	0.38
120	1.27	0.09	2.24	0.40
135	1.35	0.13	2.31	0.46
150	1.44	0.18	2.42	0.50
165	1.51	0.19	2.58	0.53
180	1.58	0.20	2.64	0.57
195	1.64	--	--	--
210	1.72	--	--	0.63
225	1.78	--	--	0.66
240	1.84	--	--	--
255	1.90	--	--	--
270	--	--	--	--

A fitted calibration curve was previously constructed to determine salt concentration from conductivity and the best fit of the linear data is given below.

$$[\text{NaCl}] = 5.698 * (\text{conductivity}) - 0.134$$

Where [NaCl] has units of g/L and conductivity is measured in mS.

HOMEWORK PROBLEMS AND SOLUTIONS BASED ON THIS EXPERIMENT

Some questions which are directed towards understanding and implementation of the model equations to describe mass transfer in this experiment are provided for your use below.

- (a.) Use this data and the Level IV model equations to calculate an approximate K_m for the salt-water system for the four different cases.

- (b.) Compare the K_m values that you have obtained. Comment as to why they are different among the four cases.
- (c.) What are some of the limitations associated with these experiments to determine K_m for the solid-liquid salt-water system? Would you feel comfortable using a K_m determined in this fashion to describe mass transfer in a 1,000 L vessel? Why or why not.

Solutions:

(a.) You need some extra information about the system which has not been directly provided here. For instance, V_i^{II} is not explicitly given to you. It is possible to calculate this quantity by using the mass and density of the salt. Thus, for Case I, the initial volume for the salt tablets is $20g*(L/2160g) = .00926 L$

As in the text, you will need to linearize the data into the form $(1-c)^{(1/3)} = 1 - \omega t$

where $c = [(Ca^I - Ca_i^I)*V^I / (\rho^{II}V_i^{II})]$ and $\omega = [(K_m \alpha N^{(1/3)} Ca_{sat}^I) / (3\rho^{II}(V_i^{II})^{(1/3)})]$

First, use the calibration curve to convert the collected data to concentrations of salt (g/L).

$[NaCl] = 5.6979*(conductivity) - 0.134$

Where $[NaCl]$ has units of g/L and conductivity is measured in mS.

Time (s)	Case I (g/L)	Case II (g/L)	Case III (g/L)	Case IV (g/L)
0	-0.077021	-0.134	1.00558	0.150895
15	2.259118	0.093916	1.00558	0.150895
30	3.968488	0.093916	3.740572	0.492769
45	4.652236	0.093916	6.589522	0.891622
60	5.222026	0.150895	7.330249	1.176517
75	5.677858	0.207874	9.837325	1.518391
90	6.190669	0.207874	10.464094	1.803286
105	6.760459	0.264853	12.344401	2.031202
120	7.102333	0.378811	12.629296	2.14516
135	7.558165	0.606727	13.028149	2.487034

150	8.070976	0.891622	13.654918	2.71495
165	8.469829	0.948601	14.566582	2.885887

Note that in some cases, the use of the calibration curve may give negative initial salt concentrations. This is most likely due to inaccuracies within the calibration curve itself, as it is just a fit to the data. For all intensive purposes you may neglect these negative concentrations of salt in the system and approximate it to be zero. After plotting $(1-c)^{1/3}$ vs. t , the slope value should be equal to ω

Case I: 3.2×10^{-4} m/s

Case II: 1.2×10^{-6} m/s

Case III: 2.1×10^{-5} m/s

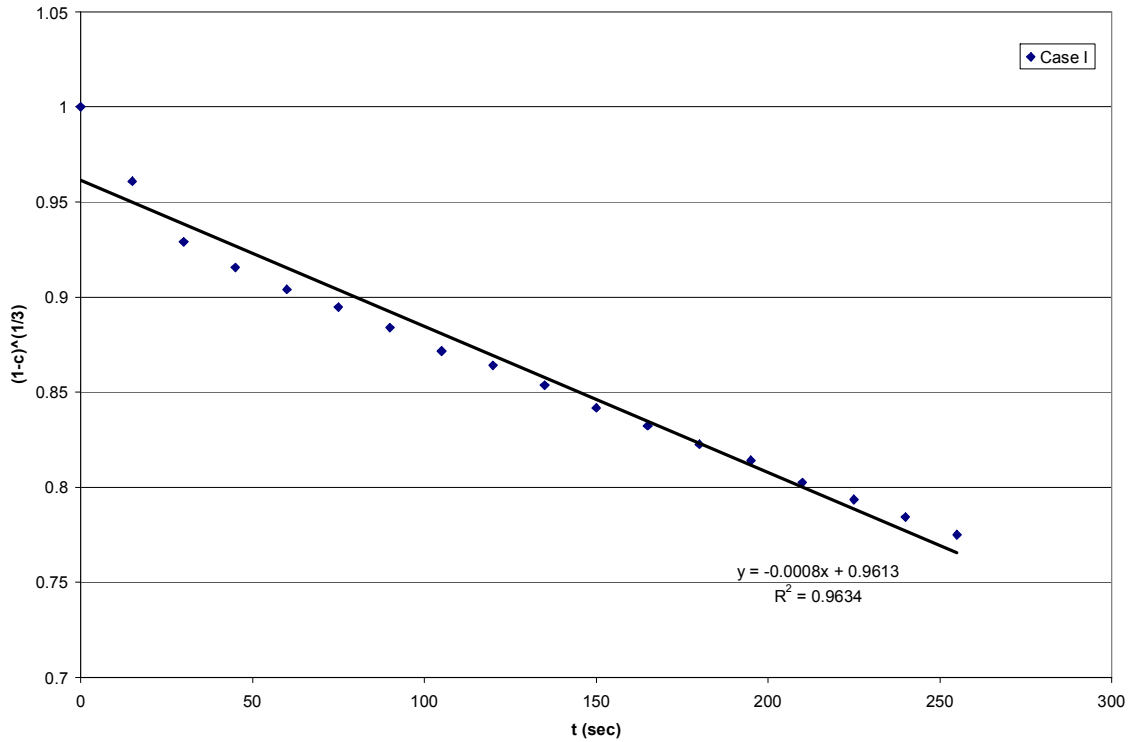
Case IV: 3.2×10^{-4} m/s

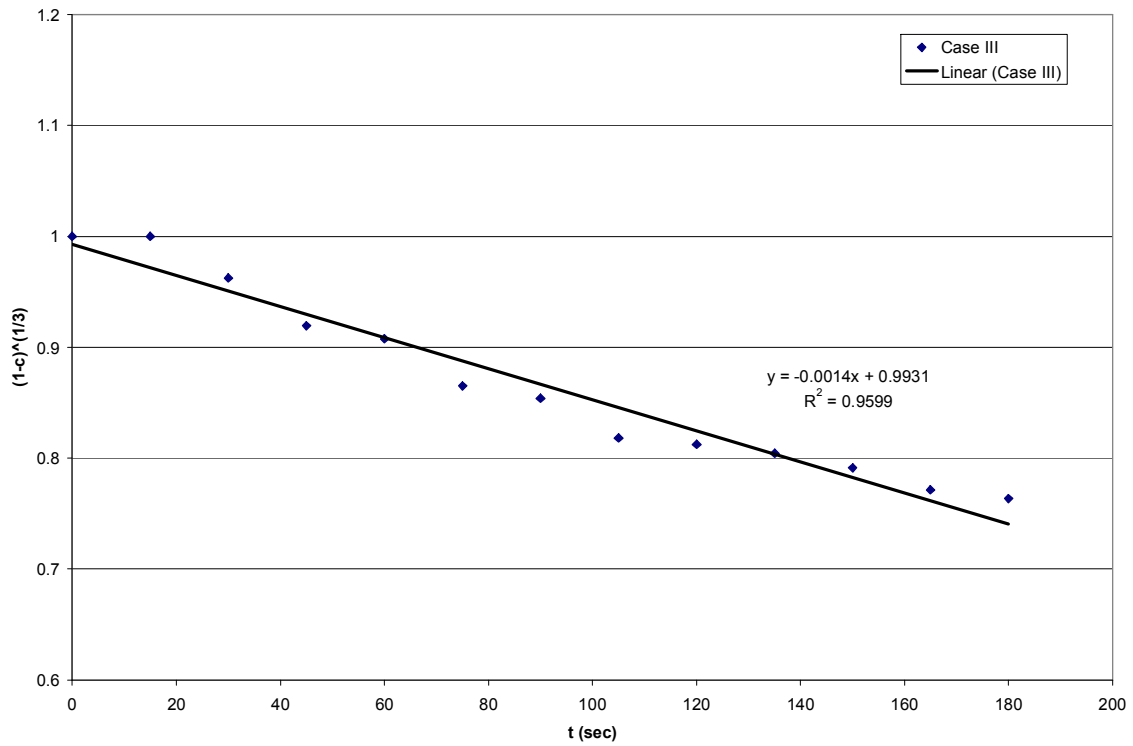
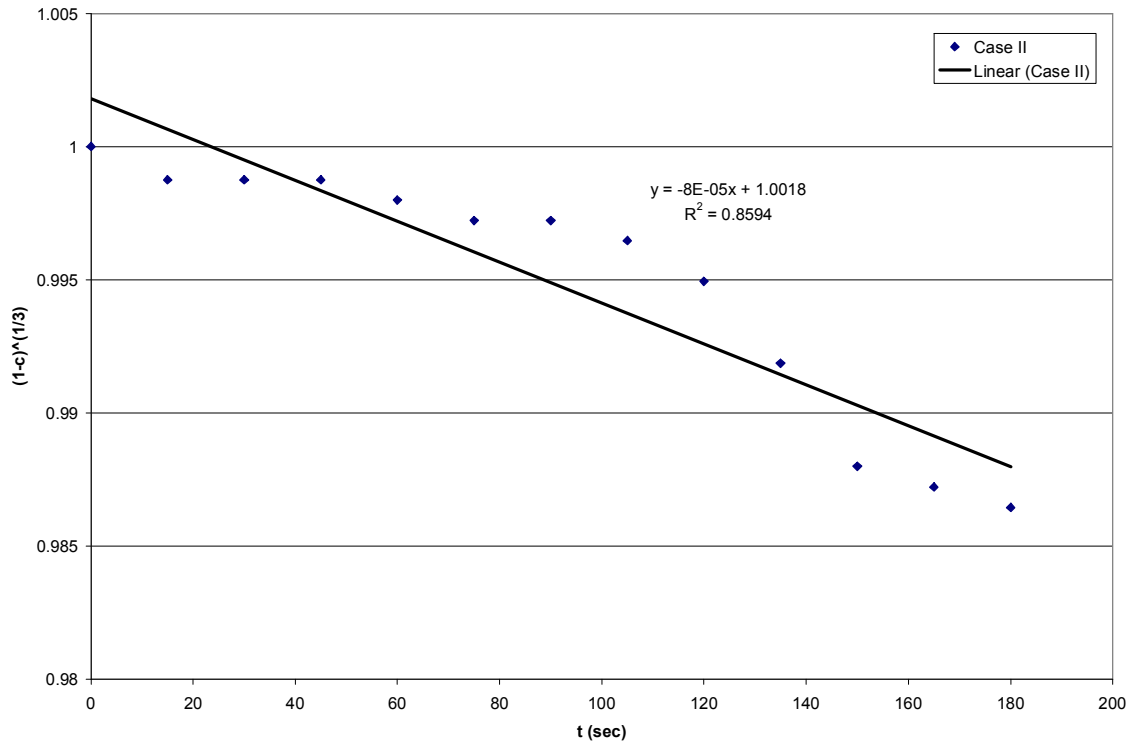
Since a fair bit of approximation must take place when dealing with the granular salt cases, these values are estimates and may vary depending on the assumptions that were made.

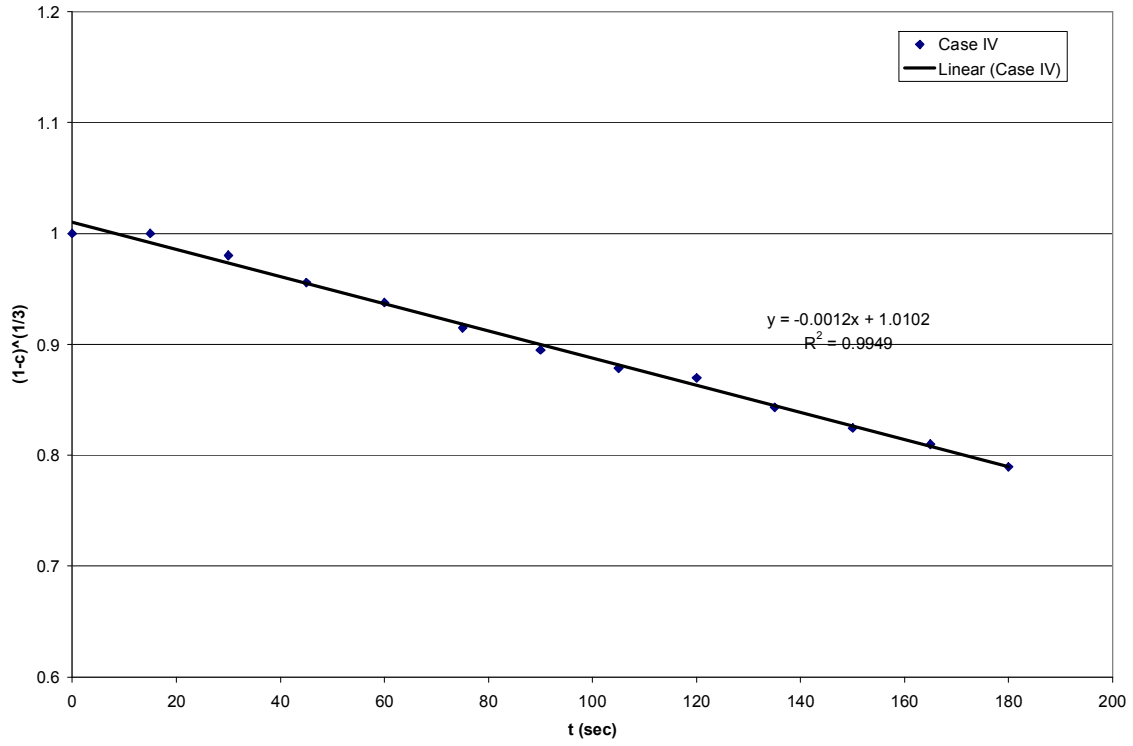
(b.) Typical values for K_m for the salt-water system are usually around 3.3×10^{-5} m/s. The Level IV equations which were used to solve for K_m have implicitly assumed a well-mixed system. Since mixing did not take place in Case II, it is not a well-mixed system, and therefore it is not appropriate to use the Level IV equations to solve for K_m . This explains why the K_m value obtained in this way for Case II is an underestimate. It is interesting to see that the calculated K_m values for Cases I and IV are similar, since salt pellets were used in those cases. These K_m values are greater than the value obtained in Case III (granular salt with mixing), and that difference is most likely due to our description of the area and volume change as mixing occurs.

(c.) Our analysis of the data assumed that we had a well-mixed system. However, our experimental apparatus consisted of a beaker with a mixing bar spinning on the bottom. It is conceivable that better mixing in the entire beaker could be achieved by an overhead impeller, or some other means. In an ideal situation, the K_m 's determined in this experiment would be directly scalable since we have not solved for $K_m \cdot a$, which is dependent on the area of mass transfer. However, our apparatus probably does not directly mimic the

apparatus that would be used in a 1,000L vessel. Also, the fluid motion within the small-scale beaker would most likely differ from that of a different mixing mechanism in the 1,000L vessel. Therefore, the K_m determined here might be a good estimate, but might not be the K_m observed in the 1,000L vessel.







ADDITIONAL HOMEWORK PROBLEMS and SOLUTIONS

Chapter 4 salt experiment homework problem:

In class, we performed some experiments to determine the overall mass transfer coefficient, K_m , in a solid-liquid batch system. Provided for you below are the data that we collected during class for salt dissolving in 1.0 L ddH₂O as a function of time, as measured through conductivity. The situations that we analyzed are given below as a reminder, and data collected from the experiments are provided in Table 1.

Case I: 5 salt pellets dissolving in ddH₂O with mixing (20g total mass)

Case II : granular salt dissolving in ddH₂O without mixing (25g total mass)

Case III: granular salt dissolving in ddH₂O with mixing (25g total mass)

Case IV: 5 salt pellets dissolving in ddH₂O with mixing (5.78g total mass)

Table 1

Time (s)	Case I Conductivity (mS)	Case II Conductivity (mS)	Case III Conductivity (mS)	Case IV Conductivity (mS)
0	0.01	0.00	0.20	0.05
15	0.42	0.04	0.20	0.05
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150	1.44	0.18	2.42	0.50
165	1.51	0.19	2.58	0.53
180	1.58	0.20	2.64	0.57
195	1.64	--	--	--

210	1.72	--	--	0.63
225	1.78	--	--	0.66
240	1.84	--	--	--
255	1.90	--	--	--
270	--	--	--	--

A fitted calibration curve was previously constructed to determine salt concentration from conductivity and the best fit of the linear data is given below .

$$[\text{NaCl}] = 5.6979 * (\text{conductivity}) - 0.134$$

Were $[\text{NaCl}]$ has units of g/L and conductivity is measured in mS.

- (a) Use this data and the Level IV model equations developed in class to calculate an approximate K_m for the salt-water system for the four different cases.
- (b) Compare the K_m values that you have obtained. Comment as to why they are different among the four cases.
- (c) What are some of the limitations associated with these experiments to determine K_m for the solid-liquid salt-water system? Would you feel comfortable using a K_m determined in this fashion to describe mass transfer in a 1,000 L vessel? Why or why not.

Chapter 4 salt experiment homework problem solution:

- Case I: 5 salt pellets dissolving in ddH₂O with mixing (20g total mass)
Case II : granular salt dissolving in ddH₂O without mixing (25g total mass)
Case III: granular salt dissolving in ddH₂O with mixing (25g total mass)
Case IV: 5 salt pellets dissolving in ddH₂O with mixing (5.78g total mass)

(d.) Use this data and the Level IV model equations developed in class to calculate an approximate K_m for the salt-water system for the four different cases.

You need some extra information about the system which has not been directly provided here. For instance, V_i^{II} is not explicitly given to you. It is possible to calculate this quantity by using the mass and density of the salt. Thus, for Case I, the initial volume for the salt tablets is $20g*(L/2160g) = .00926 L$

As we did in class, you will need to linearize the data into the form $(1-c)^{1/3} = 1-\omega t$

$$\text{where } c = [(Ca^I - Ca_i^I)*V^I/(\rho^{II}V_i^{II})] \quad \text{and } \omega = [(K_m \alpha N^{1/3} Ca_{sat}^I)/(3\rho^{II}(V_i^{II})^{1/3})]$$

First, use the calibration curve to convert the collected data to concentrations of salt (g/L).

$$[NaCl] = 5.6979*(conductivity) - 0.134$$

Were [NaCl] has units of g/L and conductivity is measured in mS.

Time (s)	Case I (g/L)	Case II (g/L)	Case III (g/L)	Case IV (g/L)
0	-0.077021	-0.134	1.00558	0.150895
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60	5.222026	0.150895	7.330249	1.176517
75	5.677858	0.207874	9.837325	1.518391
90	6.190669	0.207874	10.464094	1.803286
105	6.760459	0.264853	12.344401	2.031202
120	7.102333	0.378811	12.629296	2.14516
135	7.558165	0.606727	13.028149	2.487034
150	8.070976	0.891622	13.654918	2.71495
165	8.469829	0.948601	14.566582	2.885887
180	8.868682	1.00558	14.908456	3.113803
195	9.210556			
210	9.666388			3.455677
225	10.008262			3.626614
240	10.350136			

255	10.69201			
270				

Note that in some cases, the use of the calibration curve gives us negative initial salt concentrations. This is most likely due to inaccuracies within the calibration curve itself, as it is just a fit to the data. For all intensive purposes you may neglect these negative concentrations of salt in the system and approximate it to be zero. After plotting $(1-c)^{1/3}$ vs. t , the slope value should be equal to ω

Case I: 3.2×10^{-4} m/s

Case II: 1.2×10^{-6} m/s

Case III: 2.1×10^{-5} m/s

Case IV: 3.2×10^{-4} m/s

Since a fair bit of approximation must take place when dealing with the granular salt cases, these values are estimates and may vary depending on the assumptions that were made.

- (e.) Compare the K_m values that you have obtained. Comment as to why they are different among the four cases.

Typical values for K_m for the salt-water system are usually around 3.3×10^{-5} m/s. The Level IV equations which were used to solve for K_m have implicitly assumed a well-mixed system. Case II, it is not a well-mixed system, and therefore it is not appropriate to use the Level IV equations to solve for K_m . This explains why the K_m value obtained in this way for Case II is an underestimate. It is interesting to see that the calculated K_m values for Cases I and IV are similar, since salt pellets were used in those cases. These K_m values are greater than the value obtained in Case III (granular salt with mixing), and that difference is most likely due to the area and volume change as mixing occurs.

